Accurate Multisine Representation of Digital Communication Signals for Characterization of Nonlinear Circuits

[1]Minsheng Li, [2]Khaled M. Gharaibeh, [1]Kevin G. Gard, and [1]Michael B. Steer

[1]North Carolina State University, Dept. of Electrical and Computer Engineering, Campus Box 7914, Raleigh, NC 27695-7914 [2]Hijjawi Faculty of Engineering Technology, Yarmouk University, Irbid Jordan

***Abstract*-A technique for generating an accurate multisine representation of a digitally modulated signal using Discrete Fast Fourier (DFT) coefficients is presented in this paper. A reverse link IS-95 signal containing 200 symbols is modeled by a 240 tone multisine signal where the amplitude and phase of each tone is defined by the truncated Fourier coefficients of the original signal. Adjacent-channel power ratio (ACPR) and error vector magnitude (EVM) measurements of the multisine signal applied to a nonlinear amplifier are in excellent agreement with measurements using the IS-95 reverse link signal. This work demonstrates the accurate use of multisine signals obtained from Fourier coefficients to represent time-domain signals for analysis and measurement of nonlinear circuits.**

I. Introduction

The selection of signal excitation is of great importance in dealing with measurement and analysis of modern wireless communication systems, which utilize complex digitally modulated signals to maximize channel throughput over available channel capacity. Due to the random time-varying envelope of a digitally modulated signal, two-tone testing is not sufficient to represent signal characteristics for behavioral modeling, device and circuit testing of the wireless systems. However, traditional two-tone characterization of intermodulation distortions is well understood and more intuitive to apply to circuit analysis techniques than digitally modulated signals.

Recently much attention has been paid to periodic multisine excitations [1-4] for use with nonlinear measurements using large signal network analyzer (LSNA) equipment [5]. A multisine signal excitation consists of N equally spaced sinewaves, with random or constant amplitudes and phases. Compared to digitally modulated signals, they are easier to generate and simulate by most time/frequency domain simulators. These features render multisine stimuli considerable usefulness in behavioral modeling [1, 2], characterization of circuits and systems [4], device or system testing, and calibration of nonlinear-vector network analyzers [5].

Remley [3] examined four types of multisines each with different magnitude/phase relationships to approximate digitally modulated signals in ACPR measurement. Among the four multisines, although the multisine with a closely matched peak-to-average ratio (PAR) to the digital signal had better ACPR results, none of the multisine signals accurately predicted the ACPR of the actual digital modulation. In [1], the authors designed their bandpass multisines by matching the output power spectral density or higher order statistics of a digital signal in a general nonlinear dynamic system. One limitation of this approach is the expensive computation cost of matching the higher order signal statistics even with small amount of tones. The multisine signals from both efforts were used to primarily model out-of-band spectral regrowth distortion. They are not easily applied towards predicting waveform quality figures-of-merit such as signal to noise ratio (SNR) and error vector magnitude (EVM).

This work constructs multisine signals using the complex DFT coefficients from a realization of the digital signal by truncating the out-of-band spectral components. The amplitude and phase of each sinusoid of the multisine signal is defined by the in-band DFT coefficients. The resulting multisine excitation closely approximates the digital signals for both ACPR and EVM measurements. Tradeoffs in the number of tones required to accurately represent a particular number of symbols for a given system are discussed. A multisine representation of a CDMA reverse link signal is verified through measurements of ACPR and EVM when the signal is applied to a nonlinear amplifier. Multisine measurements are in excellent agreement with measurements using the actual CDMA signal. These results demonstrate that multisine representation of signals can be used to accurately characterize distortion and signal waveform metrics of communication signals applied to nonlinear circuits.

II. Design of Bandpass Multisines

Construction of multisines from Fourier coefficients begins by defining a bandpass multisine as a finite sum of sinusoids with unique amplitudes and phases

$$x(t) = \sum_{j=-(N-1)/2}^{(N-1)/2} A_j \cos\left[2\pi \cdot (f_c + j \cdot \Delta f) \cdot t + \theta_j\right] \quad (1)$$

where N is the number of sinusoids, A_j is the amplitude, f_c is the carrier frequency, Δf is the frequency spacing, and θ_j is the phase. The design goal is to determine the four parameters, N, A_j, Δ_j, θ_j.

Recall that a discrete signal $x(n)$ can be represented by its DFT coefficients as:

$$x(n) = \frac{1}{N}\sum_{k=0}^{N-1} X(k) \cdot e^{j2\pi kn/N} \qquad n=0,1,2,\ldots,N-1 \quad (2)$$

where $X(k)/N$ are the normalized DFT coefficients of $x(n)$. Equation (2) can be rewritten in the form as

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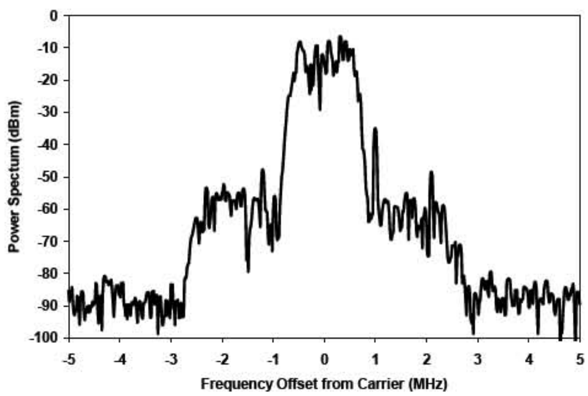
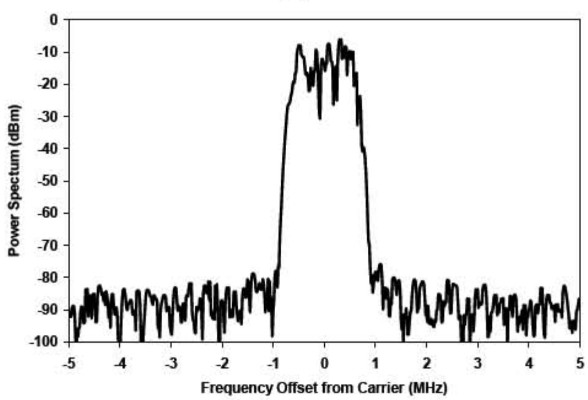
$$x(n) = \sum_{k=0}^{N-1} A_k \cdot e^{j(2\pi kn/N+\theta_k)} \qquad n=0,1,2,\ldots,N-1 \quad (3)$$

where $X(k)/N = A_k.e^{j\theta_k}$. This means a discrete signal $x(n)$ is equivalent to a sum of sinewaves whose amplitude and phase are defined by the DFT coefficients of the signal and frequency spacing is determined by the frequency resolution of the DFT. Thus a multisine representing sampled signal can be constructed in a straightforward way by using the DFT coefficients to define the amplitude, phase, and frequency spacing of the tones.

One drawback to use DFT coefficients is that a signal with N sample points will yield N DFT coefficients which results in a large number of tones required to represent the sampled signal. However, careful examination of the power spectrum of the RF signals shows that the majority of the total signal power is contained within a small fraction of the total bandwidth of the DFT, as shown in Figure 1.a which is the power spectrum of an IS-95 reverse-link signal. The information content out of this band energy is negligible. The total number of tones necessary to represent the signal is greatly reduced if the out-of-band coefficient can be neglected.



(a)



(b)

Figure 1: Power spectrums of IS-95 reverse-link signal (a) and the equivalent multisine signal (b).

The impact of truncating the bandwidth was quantified by investigating the rms error introduced by discarding the out-of-band spectral components. The normalized truncation bandwidth is defined as the ratio of the truncated bandwidth to the modulation bandwidth of the information signal. For instance, the signal modulation bandwidth of a reverse link IS-95 signal is 1.2288 MHz. The truncated bandwidth was decided by comparing the root-mean-squared (RMS) percentage errors between the real IS-95 signal waveform and the equivalent multisine waveform for different truncated bandwidths. The RMS percentage error was calculated as

$$ERR_{rms}(\%) = 100 \cdot \sqrt{\frac{\sum_{k=1}^{N}(w_k - x_k)^2}{\sum_{k=1}^{N}(w_k)^2}} \qquad (4)$$

where w_k is the IS-95 signal waveform, x_k are the time samples of the multisine signal waveform obtained from a inverse DFT (IDFT), and N is the total number of time points. The RMS percentage errors for different normalized truncated bandwidth are shown in Figure 2. The RMS percentage error decreases with an increase of truncated bandwidth and it is acceptable around the normalized truncated bandwidth of 1.2, which makes results in a 240-tone multisine representing a 163us IS-95 reverse-link signal in this paper. The spectrum of the multisine constructed with 240 tones is presented in Figure 1(b).

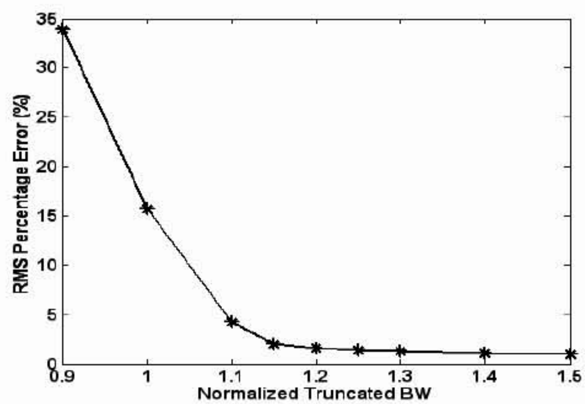


Figure 2: RMS percentage error vs. normalized truncation bandwidth.

Since the frequency, amplitude, and phase are available from the DFT coefficients and sampling frequency, the key design parameter is the number of sinewaves needed to accurately represent the original signal. The number of tones is decided by two factors: the resolution BW which is inversely proportional to the length of the signal, and the truncated bandwidth. For example, if 1 MHz bandwidth is truncated for reconstruction of signals and the frequency resolution is 10 kHz, the number of tones will be (1 MHz)/(10 kHz)=100.

In designing the multisine for the IS-95 reverse-link signal, the signal length was decided by monitoring its statistical properties. The length needs to be long enough so that statistical properties of this realization such as probability density function (PDF), power spectrum density (PSD) should have a good match with a long-duration signal. In this work a signal length of 163us (i.e. frequency resolution is 6.144 kHz) was used to reproduce a multisine for the IS-95 reverse-link signal, corresponding to 800 sampling points with a 4x1.2288 MHz sampling frequency. The signal length was selected to make the frequency resolution be an integer to avoid frequency errors. The frequencies of the bandpass multisine were calculated by a frequency translation from the baseband to carrier frequency [6].

III. Measurement Results

The accuracy of using the multisine signal representation was assessed by measurements comparing an IS-95 reverse-link signal to its equivalent 240 tone multisine representation, with a normalized truncation bandwidth of 1.2, when applied to a 2GHz nonlinear power amplifier. ACPR and EVM were measured and compared for both excitations over a range of output power levels. The IS-95 standard defines the ACPR as the ratio (in decibel) of the distortion power in 30 kHz, offset by 885 kHz from the carrier frequency, and the power in the desired channel with a bandwidth of 1.2288 MHz. The EVM is the ratio of the rms power of the error vector to the rms power of the reference power. Measurement were conducted using a vector signal analyzer (VSA) to measure the power spectrum and EVM of the two signals. It is worth mentioning that to maintain consistent measurements between each signal it was necessary to trigger the measurement equipment at the beginning of each signal for the same time duration of approximately 200 data symbols.

With IS-95 reverse-link signal excitation, the 1 dB compression point of the power amplifier occurs at about 13 dBm output power level, as shown in Figure 3. The input power sweep is from -22 dBm to 6 dBm, which corresponds to 0 ~ 17.3 dBm output power range, fully covers the weak and strong nonlinear regions of operation for the device. Notice that the gain compression characteristics of the IS-95 signal are indistinguishable from the multisine signal.

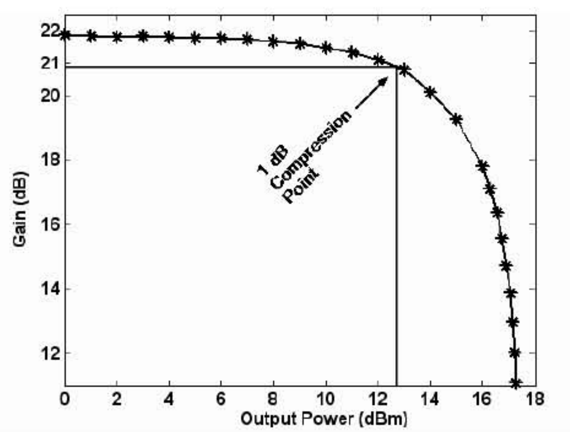


Figure 3: Gain compression characteristic of the power amplifier with both IS-95 and multisine excitations.

The IQ data of the IS-95 reverse-link signal were loaded into Agilent E4438C signal generator and carrier modulated to 2 GHz. The multisine signal was loaded into the signal generator using Agilent Enhanced Multitone signal studio which defines a multisine signal by the power, phase, and frequency of each tone.

ACPR measurement results are presented in Figure 4. The ACPR measurements of IS-95 signal and its equivalent multisine match very well when the power amplifier goes into nonlinear region, especially when the PA approaches saturation. In the linear and weak nonlinear region, there are discrepancies between the two excitations at low output power levels which is due to the truncation of the out-of-band components in the multisine signal (i.e. the out-of-band rejection of the multisine is greater than the original IS-95 signal).

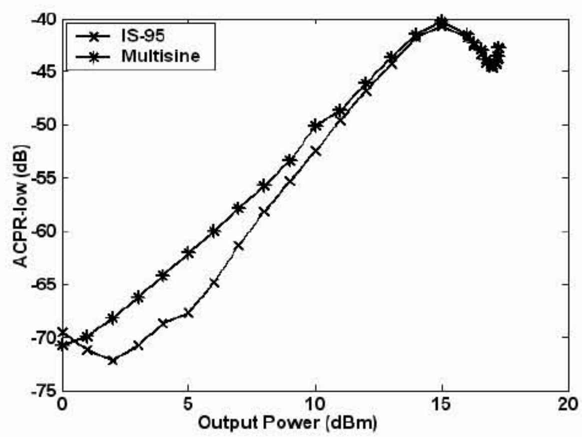


Figure 4 Comparison of measured ACPR.

The EVM measurements of the two excitations are shown in Figure 5. There is excellent agreement between the measured EVM of the IS-95 signal and multisine representation applied to the nonlinear amplifier which demonstrates that the truncated multisine signal is an equivalent representation of the original IS-95 signal. Since EVM is related to the in-band distortion, therefore, the multisine can accurately predict the in-band distortions of the original signal. The EVM decreases from the first maximum point because the PA is entering the saturation region. The minimum EVM is limited by the measurement noise floor of the signal source and the dynamic range of the VSA equipment.

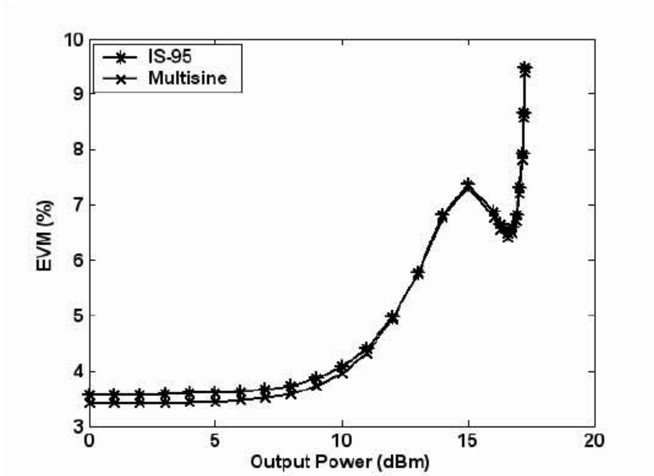


Figure 5 Comparison of measured EVM.

IV. CONCLUSIONS

This paper presented the accurate design of multisine signals using DFT coefficients to define the amplitude and phase of digitally modulated communication signals. Compared to other approaches such as signal statistical property matching, this method presents an efficient and straight forward way for generating accurate multisine signals for characterization of nonlinear circuits. An IS-95 reverse-link signal was employed to demonstrate this approach. Measured ACPR and EVM of an IS-95 and equivalent multisine signal applied to a nonlinear power amplifier are in excellent agreement. The results showed that the DFT generated multisine can very accurately predict the ACPR and EVM of the original digital modulated signal.

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